



Analysis of Russian "Vertex" High-Strength Glass Fiber

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and Matthew S. Burkins

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Analysis of Russian “Vertex” High-Strength Glass Fiber

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Abstract

This report presents the results of mechanical and ballistic tests required in MIL-PRF-46197A (U.S. Department of the Army, "A Laminate, High Strength Glass Fiber Reinforced Polyester Resin," U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 16 April 1997) on Russian Vertex high-strength glass that is supposed to be equivalent to domestic S-2 glass. The results of tensile tests of 250-yield yarns of both types of fibers were very similar, with the Vertex glass possibly as much as 2% stronger. For fabricating composites, however, a pseudo-250-yield yarn made by combining three 750-yield yarns was woven to make the fabrics used in the polyester resin composites for the mechanical and ballistic tests. This pseudo-250-yield yarn was about 7% weaker than the true 250-yield yarns. The tensile strength of the composites and the ballistic performance vs. a 20-mm fragment-simulating projectile (FSP) were both below the requirements of the specification, probably as a consequence of the use of this weaker yarn. The flexure and shear properties of the composites just met the specification, while the compressive strength was about 12% low. These results suggest that the sizing needs some fine-tuning to improve the performance of the Vertex glass fibers.

Acknowledgments

A number of people contributed to this effort. Mr. Richard O'Meara of ROM Development Corporation was instrumental in setting up the acquisition of the Vertex glass used in this project. Mr. Timothy Collins of Advanced Glass Fiber Yarns provided S-2 glass yarns for test. Mr. David Chandlee and Mr. Timothy O'Shea of the University of Delaware helped with the sample fabrication and testing the yarns. Mr. Jeffrey Swab of the Metals and Ceramics Branch of the U.S. Army Research Laboratory (ARL) performed the Weibull analyses on the tensile test results on the yarns. Mr. Donovan Harris and Mr. Phillip Patterson of the Polymers Research Branch of ARL performed the energy-dispersive x-ray analysis (EDAX) and infrared (IR) measurements, respectively. Ms. Linda Ghiorse, Mr. Paul Moy, Mr. Steven Ngyuen, and Mr. Alan Teets of the Polymers Research Branch helped set up the mechanical test equipment. Ms. Eleanor Deal, Mr. William Edmanson, and Mr. Bernard McKay of the Lethal Mechanisms Branch conducted the 20-mm fragment-simulating projectile (FSP) ballistic testing at Experimental Facility 110G. Mr. Donald Little and Mr. Vaughn Torbert of the Armor Mechanics Branch conducted the 0.22- and 0.30-cal. FSP testing at Experimental Facility 108. Ms. Mary Adamson of the ARL Foreign Intelligence Office helped obtain valuable funding for this project. These contributions are deeply appreciated.

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1. Introduction

High-strength S-2 glass has become a very important material for structural and armor applications on military ground vehicles. This glass is significantly stronger and about seven times as expensive as the cheaper and more common fiberglass known as "E" glass. The S-2 glass has been used in the structural armor employed on the composite infantry fighting vehicle (CIFV) and more recently in the composite armored vehicle (CAV) advanced technology demonstrators. Future armored vehicles, such as Crusader, will also use substantial quantities of the S-2 glass. Its importance should increase significantly as the Army develops lighter armored vehicles that are more mobile and have better survivability features.

The only U.S. manufacturer of S-2 glass, Owens-Corning, has recently sold its S-2 glass business unit to a joint venture with a French company, Porcher.* Owens-Corning has also sold their recently developed new glass fiber known as "Zentron," which is nominally stronger and cheaper than S-2 glass, to the same joint venture. Another French Company, Vetrotex-St. Gobain, makes a product known as RH glass that has been shown to have properties equal to those of S-2 glass [1]. However, Vetrotex-St. Gobain has been unwilling to market their RH glass in the United States. With the end of the Cold War, a Russian company, AO-Steklonit,† began to market an S-2 glass equivalent known as "Vertex HSG" outside of Russia. It has a chemical composition nominally identical to that of S-2 glass and, if properly made, should have strength and dielectric properties similar to those of S-2 or RH glass. The Vertex glass will nominally meet military requirements for type IV, class 1 S-2 glass fibers as specified in MIL-R-60346 (MR) [2]. This specification has recently been canceled, however. In any case, a more relevant question is how the glass fiber will perform in composite laminates, for which MIL-PRF-46197A [3] applies. Tests on composite panels made from the Vertex glass have not previously been conducted by an Army laboratory.

* Advanced Glass Fiber Yarns, 2556 Wagener Road, Aiken, SC 29801.

† AO-Steklonit, Baschkortostan, UL Tranvainaja, 15, Ufa 450040, Russia. A U.S. representative is Mr. Richard O'Meara, ROM Development Corporation, 136 Swineburne Row, Brick Market Place, Newport, RI 02840. Mr. O'Meara was instrumental in setting up the acquisition of the Vertex glass used in this project.

This report presents results of an evaluation of the mechanical and ballistic properties of the Russian Vertex glass that was conducted to determine how well it compares to the S-2 and RH glasses in polyester resin matrix composites. The results are important; if the Vertex glass tests out well and political conditions are favorable, it could easily become an economic competitor for S-2 glass, which would lead to lower prices. An additional source of material would be desirable in view of the reluctance of Vetrotex-St. Gobain to compete in the U.S. market. History has shown that economic competition is the most reliable means of driving prices down. If the glass were to test out poorly, this will also be useful intelligence information since the glass will probably be marketed worldwide. Many potential programs depend on the quality and availability of high-strength glass fibers.

The strength properties of glass fibers and composites made from them depend, in part, on the type and manner of application of protective coatings, known as sizings, that are applied to the fibers. The sizing also controls the binding of the matrix polymer to the glass in composites. AO-Steklonit claims that their C-96 sizing performs as well as the standard Owens-Corning type-463 sizing, and that they were actually developed by the same person. The sizing should enable enough matrix resin to glass fiber bonding for good mechanical strength and still allow the composite to perform well in ballistic tests, dissipating energy from the projectile by delaminating. A simple test of the sizing was also conducted to see how well the two sizings compared.

The quality of Russian material in general is widely regarded as highly uneven. The glass purchased is supposedly the best the Russians have ever marketed.

2. Material Acquisition

A total of 300 yd of 24-oz/yd² glass fabric in a 5 × 5 plain weave pattern was ordered for this project. Figure 1 shows a photograph of a piece of the fabric. This fabric style is usually made using a yarn that is sufficiently thick so that 1 lb of the yarn is 250 yd long (hence a 250-yield

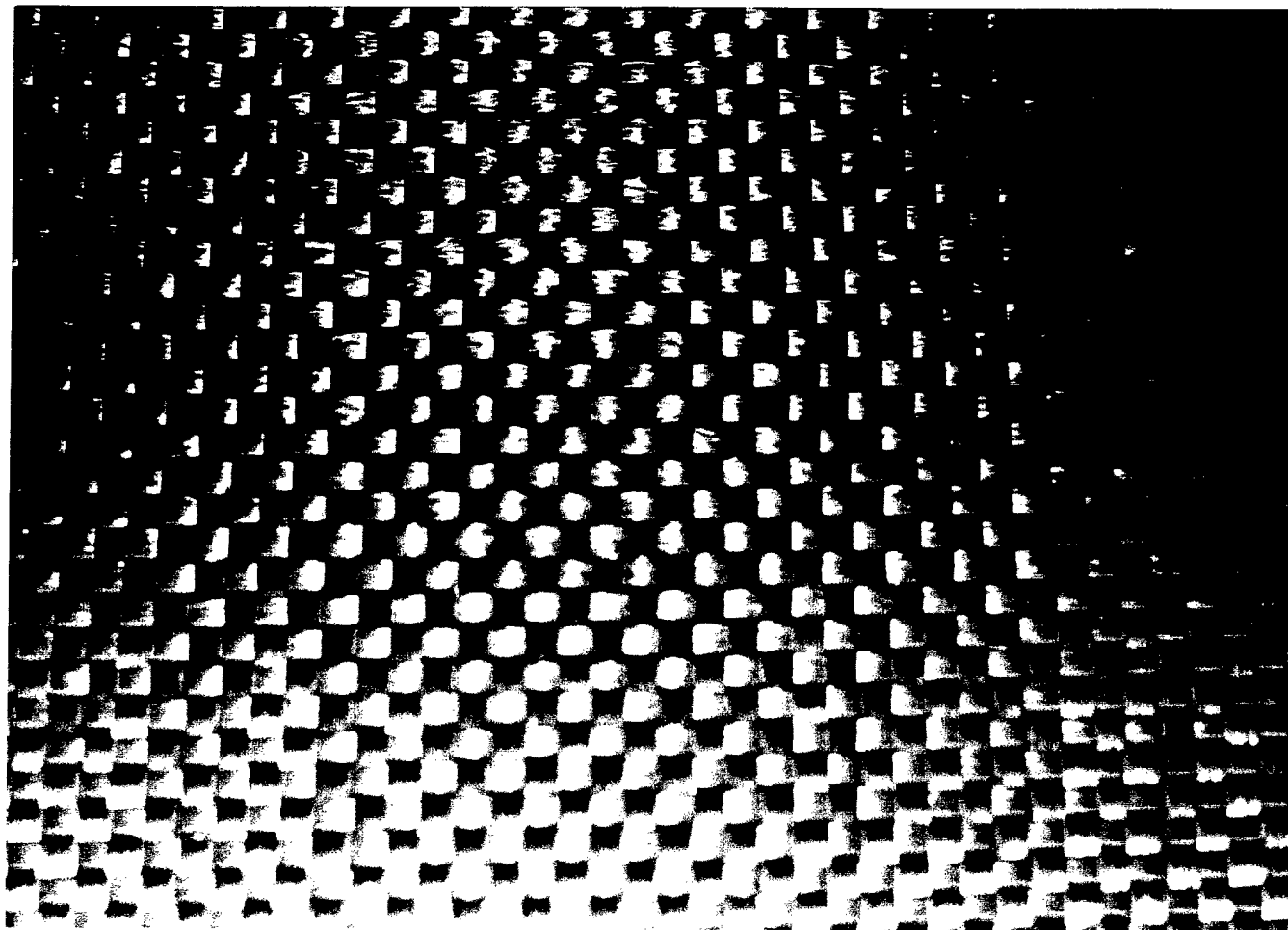


Figure 1. A Photograph of the Vertex Glass Fabric Used in This Project.

yarn). Sufficient 250-yield yarn was fabricated by AO-Steklonit for this project. However, the amount of sizing on the fiber was deemed too great for good mechanical and ballistic results to be obtained and the 250-yield yarn was not released to the weaver. After several months, it became clear that production of additional 250-yield yarn with the desired sizing by AO-Steklonit was not likely to happen in a time frame commensurate with the requirements for this project. Accordingly, a decision was made to use an alternate approach to making the fabric with three 750-yield yarns combined into a pseudo-250-yield yarn. This process involves more handling of the glass fibers, so there is the possibility of more handling damage to the fibers. Fabrics made from these fibers could have inferior strength properties. MIL-PRF-46197A [3]

allows for the use of these fabrics with the consent of the acquiring activity. Composite Materials, Inc.,* did the weaving. A sample of the fabric weighed 23.8 ± 0.1 oz/yd², well within the 24 oz $\pm 3\%$ allowed by the specification.

Approximately 300 yd of the Vertex glass fabric was prepregged by Cytec-Fiberite[†] using CYCOM 4102 polyester resin. This resin has been used extensively by the U.S. Army Research Laboratory (ARL) for the past 15 year. MIL-PRF-46197A [3] requires a number of tests on the prepreg. The volatile content, determined by weighing small pieces of prepreg before and after a 10-minute heating to 250° F in air, was found to be 2.10 ± 0.3 weight-percent, within the 0–3% allowed by the specification. Similarly, the resin content of the prepreg was determined by weighing small pieces of prepreg before and after a 2-hour heating to 1,000° F in air and subtracting the volatile content. The resin content was found to be 34.0 ± 0.4 weight-percent, in excellent agreement with the $34 \pm 3\%$ allowed by the specification. The prepregger's certificate of compliance was accepted for the other tests of the resin required in the specification. Cured composites of the prepregged Vertex glass were a little darker than similar cured composites of prepregged S-2 glass, as the photograph of the samples in Figure 2 shows.

3. Chemical Composition and Sizing Chemistry

The Vertex and S-2 glasses have the same chemical compositions according to vendor's literature. An energy-dispersive x-ray analysis (EDAX) was performed on the two glasses to see if there were any significant differences between them. None was found for the major metallic elements magnesium, aluminum, and silicon at about 2, 8, and 25 weight-percent, respectively. The Vertex glass did show traces (1 weight-percent or less) of potassium, calcium, titanium, and iron that did not show up in the S-2 glass. These elements, particularly potassium and calcium,

* Composite Materials, Inc., 19105 63rd Ave. NE, PO Box 25, Arlington, WA 98223.

† Cytec-Fiberite, 1440 N Kraemer Blvd., Anaheim, CA 92806.

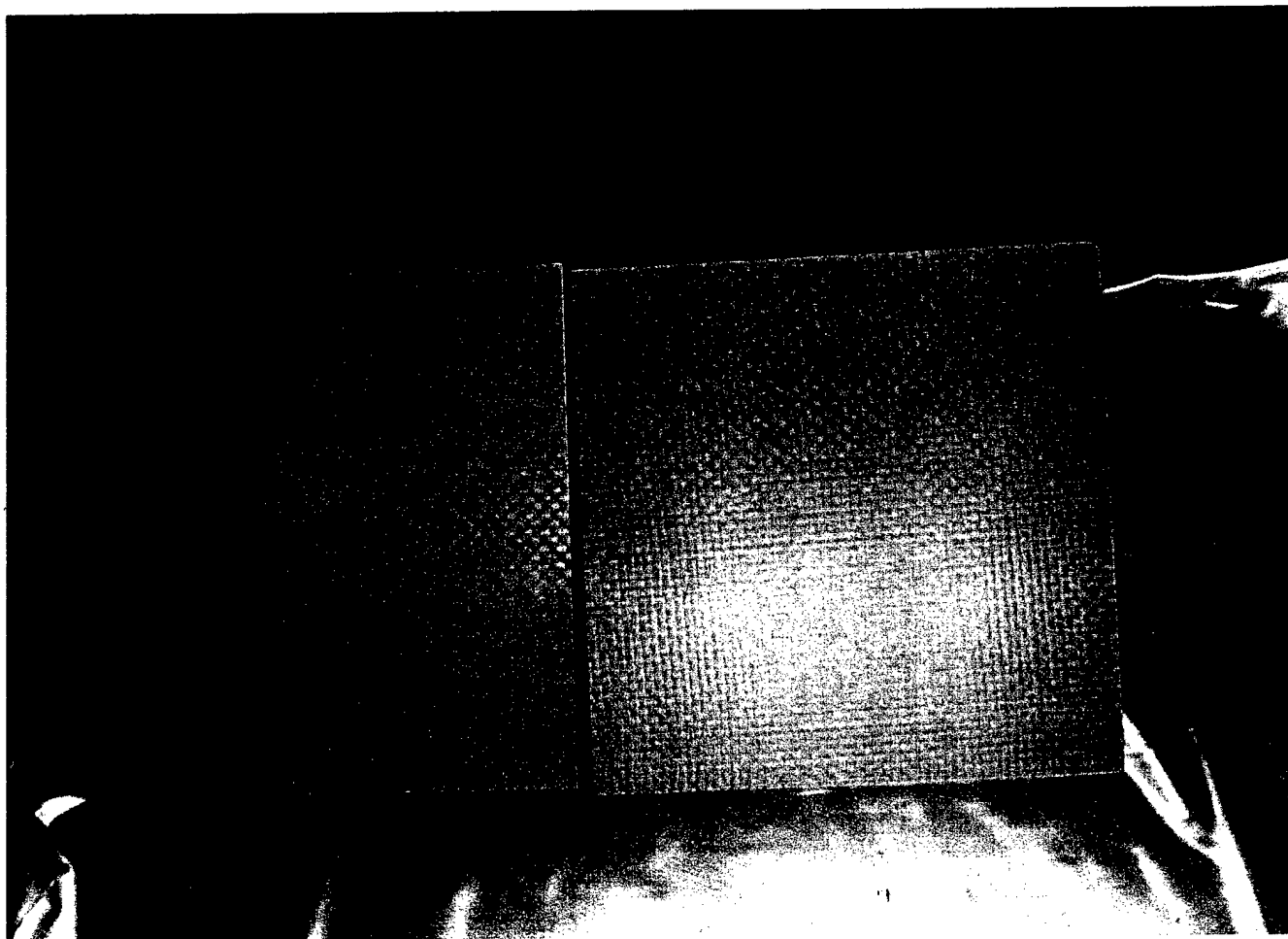


Figure 2. A Photograph of Samples of Cured, Prepregged, Vertex Glass (Right) and S-2 Glass (Left).

could lower the strength of the glass, although the tensile tests on the yarns would suggest that this was not a problem and the glass is just as strong as S-2 glass. The iron could account for the slight color difference noted in the composites.

Samples of both the Russian and domestic glass fibers were refluxed in methyl ethyl ketone to try to remove some of the sizing for infrared (IR) analysis. IR spectra of the extracts from the two fibers were similar but not identical. The spectra suggest that a bis-phenol-A epoxy is the major constituent of the sizings.

4. Tensile Tests on Glass Yarns

In order to obtain as direct a comparison between the S-2 and Vertex glass fibers as possible, tensile strength tests were run on several fiber yarns. Spools of 250-yield yarns of S-2 and Vertex glasses were obtained from Owens-Corning and Graphite Masters* (through ROM Development Corporation), respectively. A spool of the pseudo-250-yield yarn (three 750-yield yarns combined) was also obtained from the fabric weaver, Composite Materials, Inc. Owens-Corning also provided a spool of 750-yield S-2 glass yarn that was tested to see how it compared to the 250-yield yarn.

The tensile tests were run on a standard Instron[†] testing machine. The gauge length of fiber was 10 in. The yarns were held in place with a special fixture. Fifty samples of each yarn were tested so that the spread in tensile strengths could be adequately explored. The results are presented in Table 1.

Table 1. Tensile Test Results on S-2 and Vertex Glass Yarns

Yarn	Maximum Load (lb)	Weibull Load (lb)	Weibull Slope (m)
250-Yield S-2	289 ±43	304	7.77
250-Yield Vertex	295 ±39	312	8.35
Pseudo-250-Yield Vertex	274 ±34	289	8.46
750-Yield S-2	102 ±9.3	106	13.03

In view of the spread in the data, it is clearly preferable to analyze the glass fiber tensile strength data using the methodology now generally applied to ceramic materials. This methodology is described in ASTM-C-1239-95 [4]. Weibull plots of the data for the 250-yield S-2 and Vertex glasses are shown in Figures 3 and 4. The test results for these two yarns are very

* Graphite Masters, Inc., 3815 Medford St., Los Angeles, CA 90063-1900.

[†] Instron Corporation, 100 Royall Street, Canton, MA 02021.

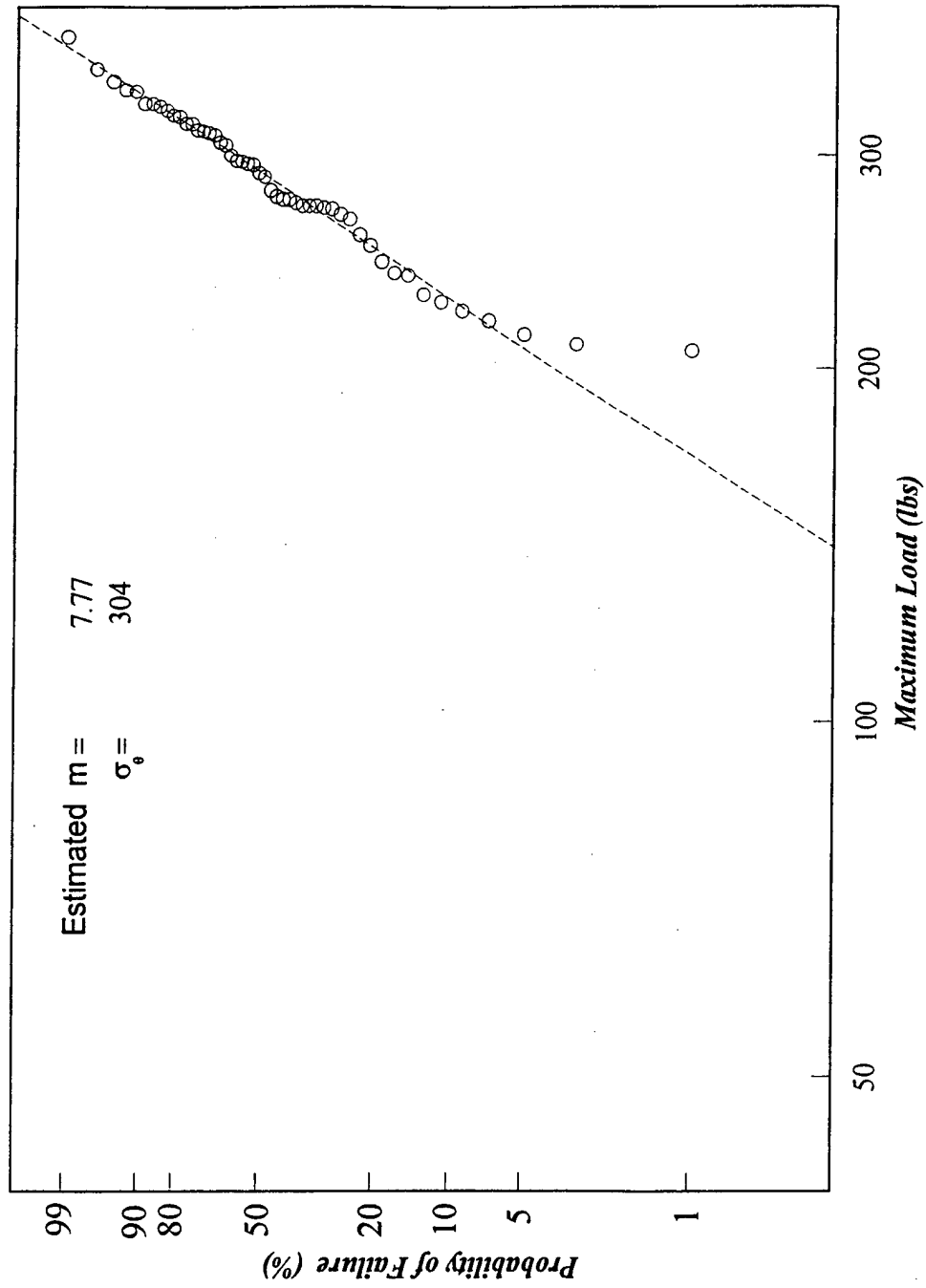


Figure 3. Weibull Plot of the Tensile Test Data for 250-Yield Owens-Corning S-2 Glass Yarn.

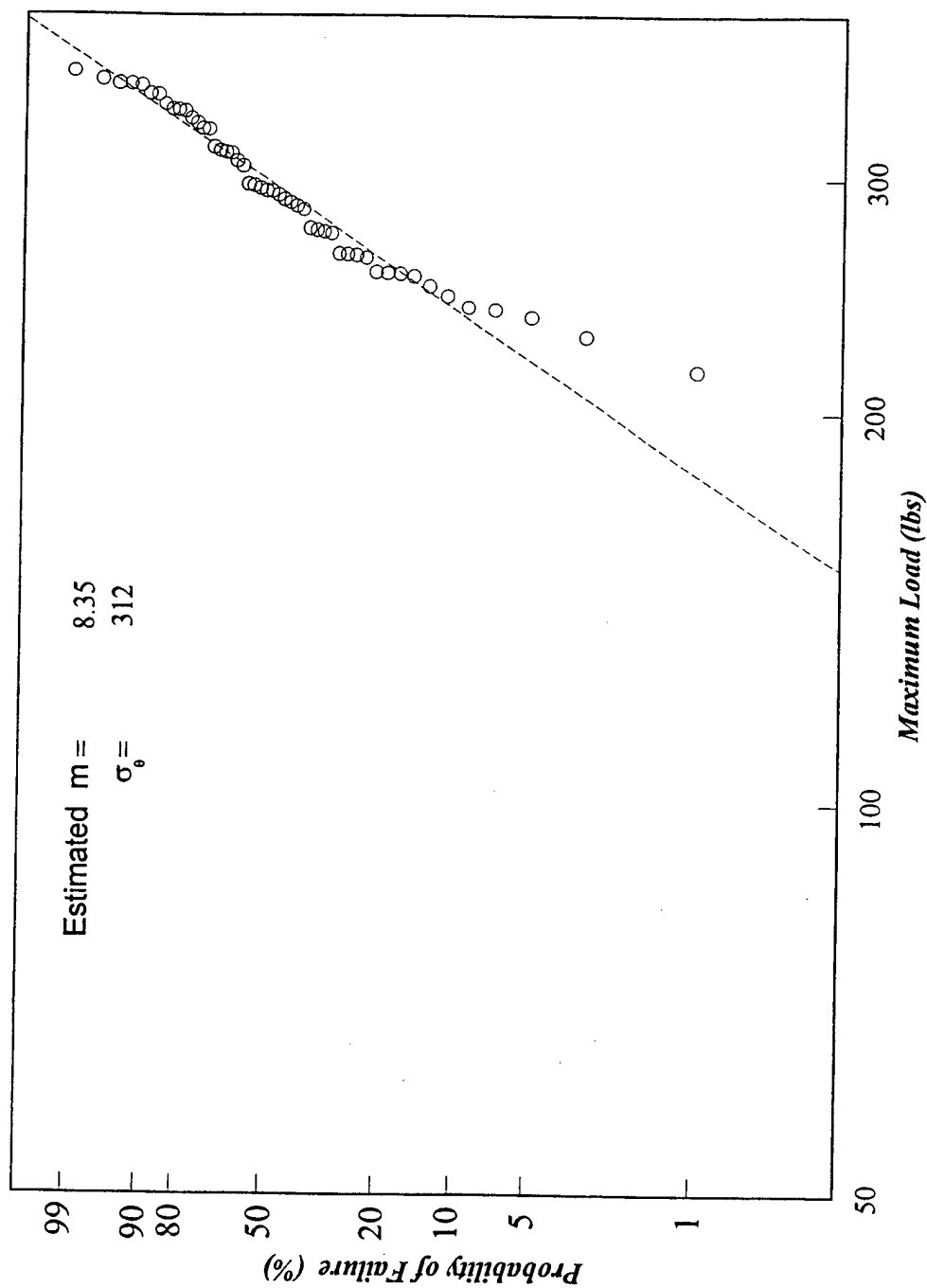


Figure 4. Weibull Plot of the Tensile Test Data for 250-Yield Vertex Glass Yarn.

similar, with the Vertex glass marginally stronger. The results are consistent with the proposition that a single flaw population with a distribution of defect sizes determines the strength of the material.

The lines in the Weibull plots represent a fit of the data to the formula

$$P_f = 1 - \exp - (\sigma/\sigma_\theta)^m,$$

where P_f is the probability of failure, σ is the strength (load in this case), σ_θ is the characteristic strength, and m is an experimentally determined constant. In general, the higher the "m" value, the narrower the distribution of strength-limiting flaws. The characteristic strength (load), σ_θ , is the load at which 63.2% of the samples have failed. The m values for the 250-yield S-2 and Vertex glasses are quite similar, as are the characteristic strengths, 304 lb and 312 lb, respectively.

The characteristic strength of the pseudo-250-yield Vertex glass is a little lower, at 289 lb, but the m value is similar to that for the 250-yield yarn (see Figure 5). This is consistent with the possibility that the additional handling required to combine the three 750-yield yarns introduces a few extra defects in the yarn. Also, having three 750-yield yarns wound together could result in a few stress concentration points that are not present in the larger 250-yield yarn.

The 7% lower tensile strength of the pseudo-250-yield fibers indicates that this method of making a 250-yield roving should be avoided if possible.

The m value for the 750-yield S-2 glass is considerably higher than that for the heavier yarns (see Figure 6). Note too that a 250-yield yarn is not exactly three times stronger than a 750-yield yarn.

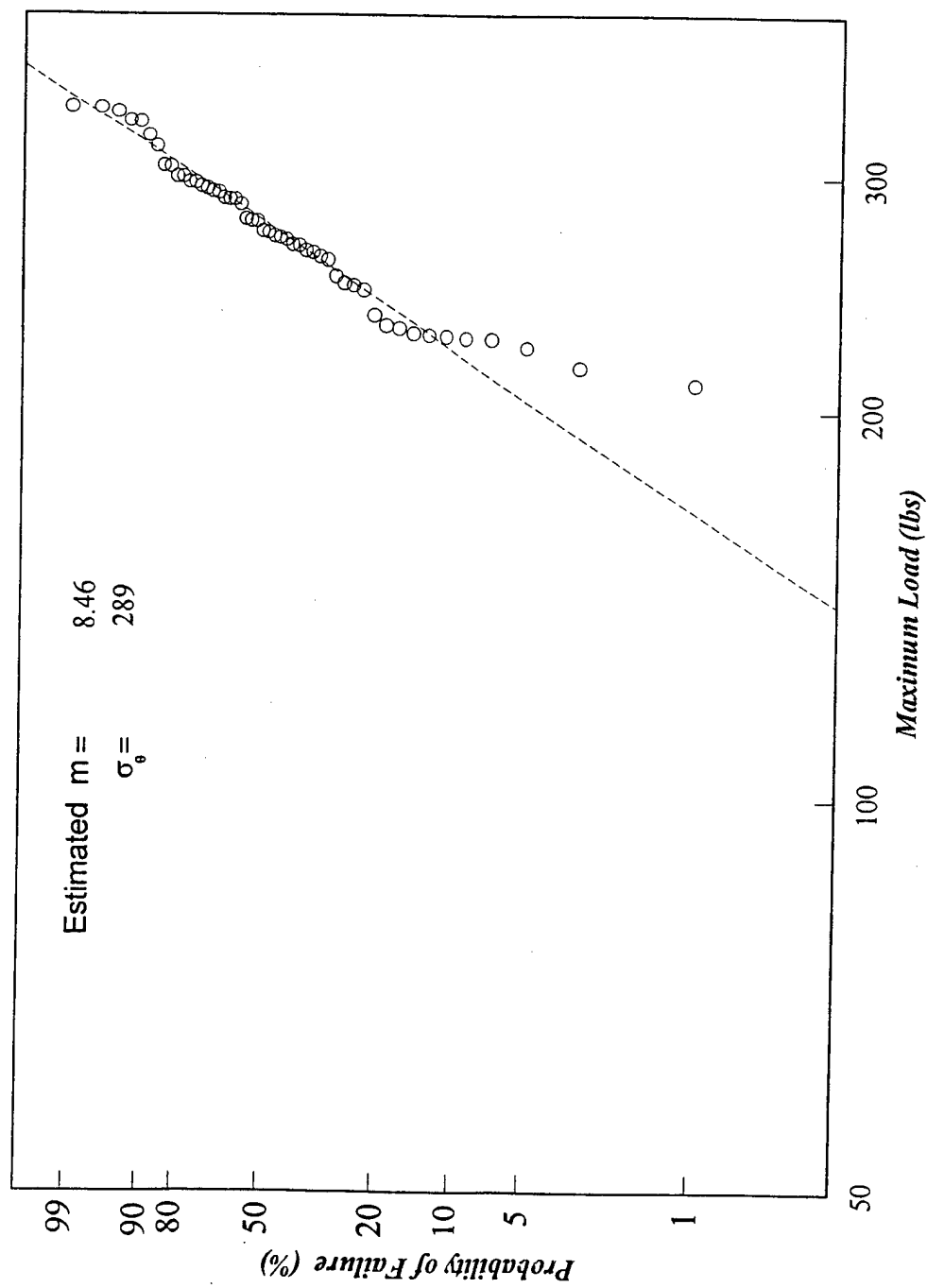


Figure 5. Weibull Plot of the Tensile Test Data for the Pseudo-250-Yield Vertex Glass Yarn (Three Combined 750-Yield Yarns).

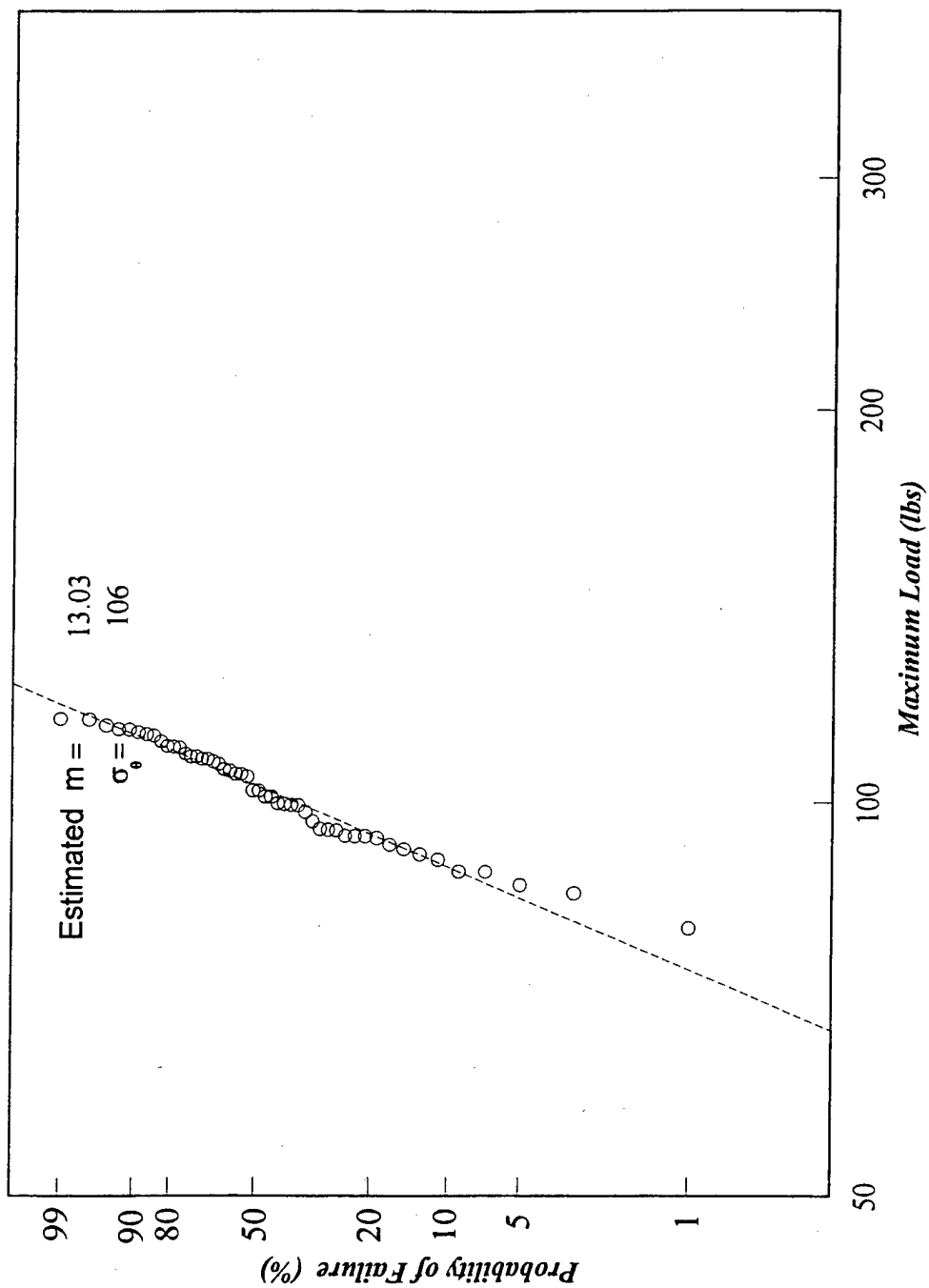


Figure 6. Weibull Plot of the Tensile Test Data for 750-Yield S-2 Glass Yarn.

5. Composite Mechanical Properties

MIL-PRF-46197A [3] and its predecessor MIL-L-46197 [5] specify a number of standard mechanical tests listed in Table 2 for glass-polyester laminates.

Table 2. Required Composite Mechanical Tests

Test	Standard
Tensile Properties	ASTM-D638 [6]
Flexural Properties	ASTM-D790 [7]
Compression Strength	ASTM-D695 [8]
Short-Beam-Shear Strength	ASTM-D2344 [9]

These tests are to be made on specimens cut from a quasi-isotropic panel fabricated with the ply sequence 0° , -45° , $+45^\circ$, 90° , 0° , 90° , $+45^\circ$, -45° , and 0° , where the angle is measured with respect to the warp direction of the fabric (the long direction of the fabric roll). This arrangement minimizes effects arising from the test specimens being cut a little off the nominal 0° direction of the panel. A 2-ft² panel was fabricated using plies from different rolls of the prepregged Vertex glass fabric. The individual plies were cut from regions of the prepregged fabric with minimal weft distortion (regions in which the 0° and 90° rovings were as close to perpendicular as possible). Care was taken not to introduce additional distortion into the prepregged fabric. The test specimens were cut to the required shapes by Dess Machine and Manufacturing.* The long axis of the test specimens was the 0° direction of the panel. Examples of the test specimens prior to testing are shown in Figure 7. A few compression test samples were also cut in-house as 0.5-in-wide \times 0.215-in-thick \times 3-in-long rectangular samples. The test results on the samples and the test requirements are shown in Table 3.

* Dess Machine and Manufacturing, 5049 N DuPont Hwy., Dover, DE 19901.

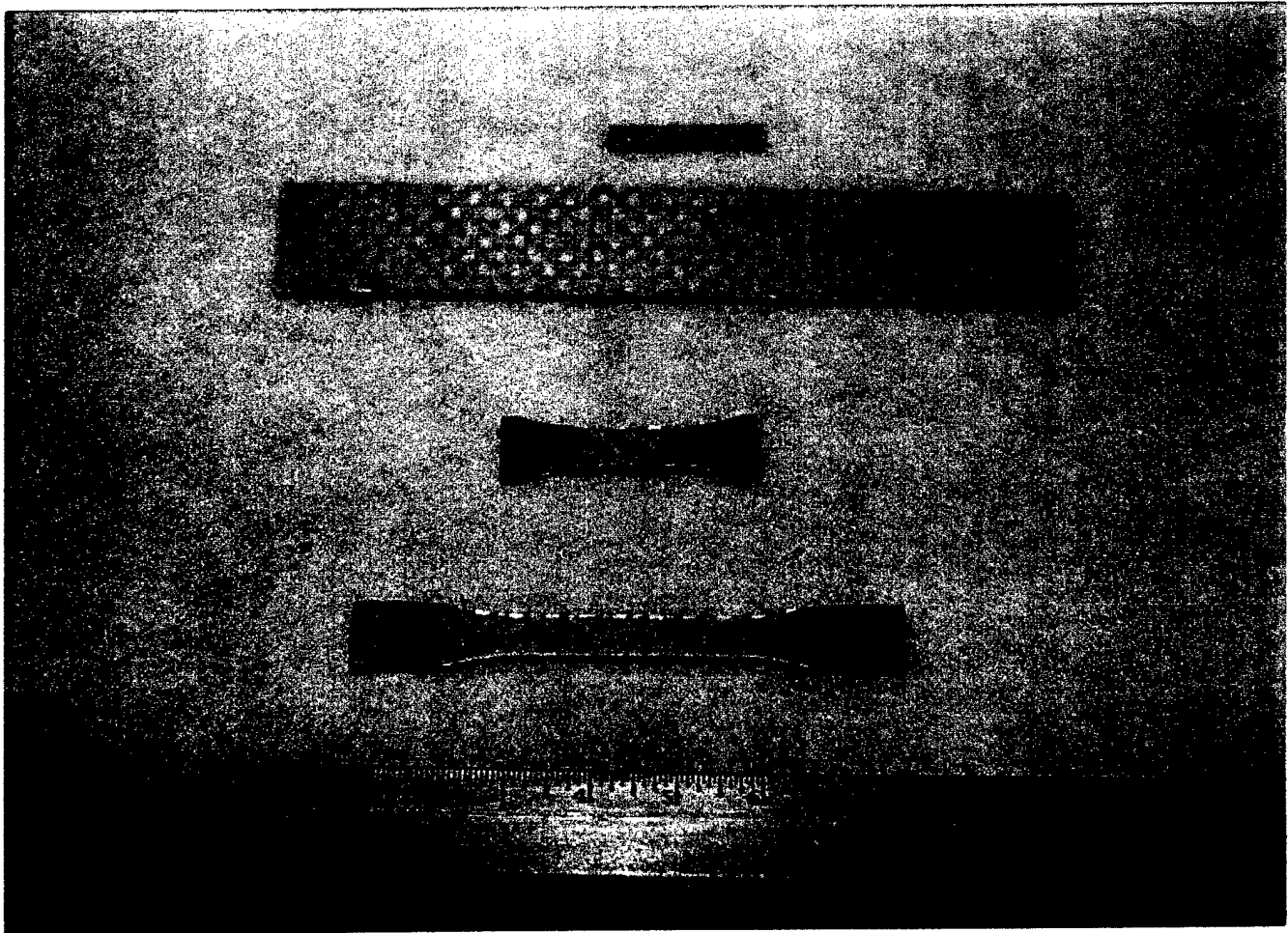


Figure 7. Test Specimens for Tensile, Flexure, Compression, and Short-Beam-Shear Tests Before Testing.

Table 3. Results of Tensile, Flexure, Compression, and Short-Beam-Shear Tests on Vertex Glass Composites

Test	Requirement	Vertex Glass
Tensile Strength (ksi [MPa])	43 [296]	40.4 \pm 2.8 [278 \pm 19]
Tensile Modulus (msi [GPa])	2.3 [15.8]	2.59 \pm 0.15 [17.8 \pm 1]
Compressive Strength (ksi [MPa])	20 [138]	17.6 \pm 0.9 [121 \pm 6.2]
Flexure Strength (ksi [MPa])	32 [221]	33.3 \pm 2.2 [230 \pm 15]
Flexure Modulus (msi [GPa])	2.5 [17.2]	2.55 \pm 0.13 [17.6 \pm 0.9]
Short-Beam-Shear Strength (ksi [MPa])	2.5 [17.2]	2.55 \pm 0.1 [17.6 \pm 0.7]

The tensile strength of the composite samples is 6% lower than the requirements of the specification. This is almost exactly the difference between the strength of the 250-yield and pseudo-250-yield rovings. It thus seems likely that a fabric made with the 250-yield roving would have passed this test. The tensile modulus just meets the requirements of the specification.

The flexure strength and modulus and the short-beam-shear strength just barely meet the requirements of the specification. Although these three properties depend strongly on the mechanical properties of the matrix resin and of the fiber-matrix interface, the test results would be higher if the fibers were stronger and a true 250-yield yarn had been used.

The compressive strength is well below the requirements, however. Several batches of samples were run to verify this result. A stronger and stiffer fiber would improve the compressive strength, but the difference between the 250-yield and pseudo-250-yield yarns is probably not large enough to bring the compressive strength up to the requirement of the specification. The results suggest that a modification in the sizing chemistry could improve all of the mechanical properties tested.

6. Ballistic Testing

For ballistic testing, MIL-PRF-46197A [3] only requires testing of a 69-ply laminate with an areal density of 17 lb/ft^2 against a 20-mm fragment-simulating projectile (FSP). The velocity at which half of the shots completely penetrate the laminate (V_{50}) should be above 2,370 ft/s to meet the specification. It is difficult to make 69-ply laminates, and the first two large panels (2 ft^2) made using the prepregged Vertex glass were failures since they exhibited serious internal delaminations. At the time, it was not clear if the failure was a consequence of poor fabrication technique (as now seems probable) or if it was due to an excessive incompatibility between the resin and the sizing. In view of this, a few additional ballistic tests seemed desirable, so tests

were also run on 10-ply panels (2.3 lb/ft²) with a 0.22-cal. FSP and against a 22-ply panel (5 lb/ft²) with a 0.30-cal. FSP.

All of the ballistic laminates tested were 1 ft × 1 ft and were shot once in the center. Laminates were clamped to a metal fixture during testing using a C-clamp at each corner. A 2024 aluminum witness plate 0.020 in thick was placed behind each laminate during ballistic tests to confirm partial and complete penetrations.

Ballistic testing of the 69-ply laminate vs. a 20-mm FSP must meet or exceed 725 m/s (2,380 ft/s). The 69-ply targets had an average areal density of 17.2 lb/ft². The results of the tests are listed in Table 4. The material came within 2% of the minimum V₅₀ of 725 m/s at the required areal density. It is probable that the glass would have passed this test if the 7% stronger 250-yield roving had been used instead of the pseudo-250-yield roving. A photograph of a panel that has been ballistically tested with the 20-mm FSP is shown in Figure 8.

Table 4. Ballistic Test Results for 20-mm FSP vs. 69-Ply Vertex Glass Composite Panels

Shot No.	Velocity ^a	Penetration	Used for V ₅₀ ^b Calculation
1	742	Complete	N
2	765	Complete	N
3	622	Complete	Y
4	724	Complete	N
5	675	Partial	N
6	695	Partial	Y
7	708	Partial	Y
8	733	Complete	N
9	719	Complete	Y
10	713	Complete	Y
11	695	Partial	Y

^a Velocity Spread: 27 m/s (88 ft/s).

^b V₅₀: 709 m/s (2,326 ft/s) ± 11 m/s (36 ft/s).

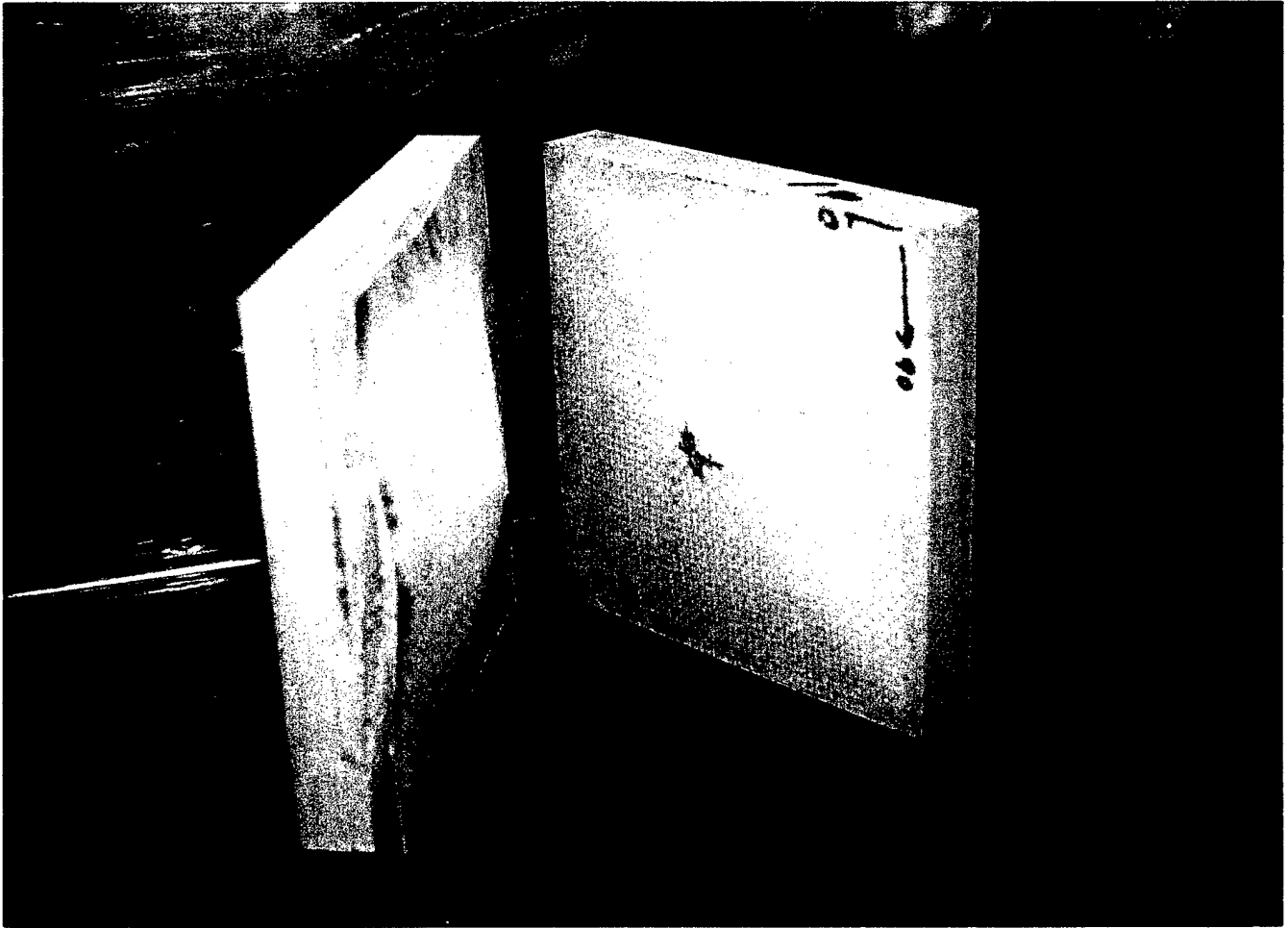


Figure 8. A Photograph of a 69-Ply Vertex Glass Laminate After Ballistic Testing With a 20-mm FSP.

In all cases, the ballistic test results for the Russian Vertex glass are not as good as those for the French RH glass reported in Haskell [1]. The V_{50} values are linear functions of the areal density of the armor and of the strength of the fibers. If the values are corrected to the areal densities of the RH glass and the 7% strength factor for 250-yield glass is taken into account, the Russian ballistic data come much closer to the RH data, as shown in the last column in Table 5.

The test results on all the thinner plates are presented in Table 5. The results of these tests are compared to results of previous ballistic tests on RH glass from Vetrotex-St. Gobain

Table 5. Test Results of Vertex and RH Glass Composites

Material	Areal Density (lb/ft ²)	Projectile Caliber and Weight (Grains)	V ₅₀ (m/s [ft/s])	Shots - Velocity Spread (m/s)	Normalized V ₅₀ (m/s [ft/s])
Russian Vertex	2.31	0.22 (17)	472 [1,548]	4-15	494 [1,620]
RH	2.26	0.22 (17)	530 [1,740]	4-16	530 [1,740]
Russian	5.22	0.30 (44)	689 [2,260]	4-34	798 [2,617]
RH	5.65	0.30 (44)	792 [2,597]	2-38	792 [2,597]
Russian	17.19	20 mm	709 [2,326]	6-27	775 [2,541]
RH	17.55	20 mm	840 [2,755]	2-13	840 [2,755]

presented in Haskell [1]. The RH glass passed all of the tests (mechanical and ballistic) required by the specification.

7. Conclusions

The Russians have developed a glass fiber that comes close to meeting the requirements in MIL-PRF-96197A [3] for S-2 glass composites. The pseudo-250-yield roving used in the composites was about 7% weaker than a true 250-yield roving in direct tensile tests on the rovings. If a true 250-yield roving had been used, it is likely that the composites would have passed all of the mechanical and ballistic tests, except for compressive strength. Some modifications to the sizing are probably needed for composites of these fibers to pass this test.

Questions must also be raised about the value of MIL-PRF-96197A [3] as a specification for qualifying high-strength fibers. The specification was written for S-2 glass fibers with a special (epoxy) sizing and resin (polyester) that could be made into composites with particular mechanical and ballistic properties that were relevant to the CIFV. The same S-2 glass fiber with a different sizing (an amino silane) was used in the structural composites on the CAV in composites based on phenolic and epoxy resins. These composites have better mechanical properties than the polyester composites and are processed by cheaper vacuum-assisted resin-transfer molding techniques. New specifications for these for composites based on these resins and fibers with an amino silane sizing are needed. The new Zentron fiber also needs to be thoroughly evaluated, since it has the potential to replace S-2 glass as the high-strength glass of choice.

The future of the Russian Vertex high-strength glass is not clear. The plant where it is made has recently been temporarily closed for lack of demand. Programs in other countries could rapidly change this situation, however. The Vertex glass fiber is reasonably good and could be made even better.

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